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Review

Material logistics in hospitals: A literature review ☆

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ABSTRACT

Hospital material management has been identified as one key cost containment lever to cope with steadily increasing healthcare costs in industrialized countries. The purpose of this work is to present the state-of-the-art of research on material logistics management in hospitals. Particular focus is given to articles that apply quantitative methods. Our contribution is threefold: First, we provide research guidance through categorizing literature and identifying major research streams. Second, we discuss applied methodologies and third, we identify future research directions. A systematic approach is undertaken in order to identify the relevant literature from 1998 to 2014. Applicable publications are categorized thematically and methodologically and future research opportunities are worked out. In total, 145 publications are identified and discussed in this work. The literature is categorized into four streams, i.e., (1) Supply and procurement, (2) Inventory management, (3) Distribution and scheduling, and (4) Holistic supply chain management. The use of optimization techniques is constantly gaining importance. The number of respective publications has continually grown and has peaked over the last three years. Optimization has been successfully applied in research streams (1), (2), and (3). Category (4) comprises a rather qualitative research field of literature dealing with supply chain management issues.

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1. Introduction

In the countries of the OECD, total healthcare expenditures have grown with an average of 4% per year from 2000 to 2009 [127]. Hospitals account for 29% of total healthcare expenditures [128]. Of hospital costs, more than 30% are linked to logistics activities [122]. This makes logistics costs the second largest cost block after personnel costs [138,148]. Compared to other industries, material management and logistics have not been given high priority in hospital management research in the past. Possible reasons are the high complexity of healthcare supply chains and their merely supporting role in the foremost goal of hospital management, i.e., effective treatment of patients [13]. However, in the last fifteen to twenty years, logistics has been identified as one key lever to manage healthcare costs [164,33]. Research estimates that through efficient logistics management, around half of the logistics-related costs in hospitals can be eliminated [138].

The potential of hospital logistics optimization within the healthcare sector is considered significant both by academia and practitioners. The most obvious upside from optimizing material logistics is that cost reductions do not directly affect the quality of patient care [78]. In contrast, logistics-related activities are often performed by medical staff, taking away time from taking care of patients. In a recent survey among registered nurses in the U.S., time wasted on activities other than patient care, such as restocking supplies, was the major driver that negatively impacted nurses' time at bedside [75]. Relieving nurses from non-patient care related activities can thus improve the quality of care.

The aim of this work is to present the state-of-the-art of research on material logistics management in hospitals. In the discussion, we set a distinct focus on publications that apply quantitative methods. Respective papers are discussed in detail, e.g., by providing tables with deep-dive analyses on the applied methodologies. Our contribution is threefold: First, we provide research guidance by categorizing the literature and identifying major research streams. Second, we discuss applied methodologies and third, we identify future research directions. There exist rather general literature reviews on healthcare operations research/operations management (e.g., [42,68,141]). Also, a number of reviews exist on supply chain management (SCM) in healthcare, e.g., de Vries and Huijsman [165], who focus on the question whether or not there exist parallels between the industrial sector and healthcare services. Dobrzykowski et al. [38] thematically assess a more general scope than this work as they include operations management topics like service management, planning, and scheduling. Furthermore, they limit their review to publications from seven U.S. journals only and review a different time period (1982 to 2011). Consequently, to the best of our knowledge, there is currently no comprehensive review on material logistics in hospitals with a focus on quantitative methods. This publication fills the research gap.

The remainder of this article is structured as follows. Section 2 presents the methodology of the literature review and introduces a framework to cluster the relevant literature thematically. Section 3 provides a quantitative overview of topics, applied methodologies, and the regional coverage of assessed publications. Furthermore, an overview of all publications is provided. Sections 4–7 discuss the literature along this framework and point out future research potential. We present a conclusion and a summary of research opportunities in the final section.

2. Methodology

2.1. Scope

This paper reviews all relevant publications regarding the logistics activities of handling physical goods in hospitals. Physical goods comprise all items that are directly linked to the care of patients, like pharmaceuticals, medical consumables, food, laundry, sterile items, laboratory samples, waste, etc. Pharmaceuticals represent 70% to 80% of the supply costs, while medical-surgical materials account for 20% to 25% [142]. Non-patient care related products, e.g., office supplies, mail, etc., are excluded. Further, although partly included in logistics activities, flow of information is excluded. Due to its distinct characteristics, such as the irregularity of supply and the lacking comparability to the items stated above, blood products are out of scope of this review. Comprehensive reviews on SCM of blood products are available in the literature [149,15]. Considering the supply chain of goods from manufacturing to use, this review starts with the supply chain partners one step upstream from the hospital, i.e., typically the hospital-supplier interface. One exception is Section 4.4, where we shed light on the interface between drug manufacturers and wholesalers and implications for hospital purchasing. Also, reverse logistics is not in particular scope of this publication, however we refer to Srivastava [152] for designing a reverse logistics network. Logistics activities associated with outpatient treatment, like home delivery of meals or outpatient medication, are out of scope. Exemplarily, Liu et al. [104] present related work. Our restriction of scope is in line with existent literature, as hospital-internal logistics activities are the major source of competitiveness within healthcare material management [144,97]. Personnel planning and scheduling that is not directly related to logistics activities as well as bed and patient transportation are out of scope of this work.

2.2. Identification of publications

In order to identify the relevant literature, a five-step approach is undertaken. First, Google Scholar and Science Direct are searched for relevant keywords, e.g., "hospital" and "logistics". Second, a forward and backward search of the most relevant publications is performed. Third, the categorization framework presented below is developed and the literature is classified accordingly. Fourth, another Google Scholar and Science Direct search applying relevant key words within the respective category is done. Fifth, a final forward and backward search within those publications concludes the search process. We limit our research to English articles published in peer-reviewed journals. Books, theses, PhD dissertations, conference articles, and working papers are neglected. A focus is set on publications after the year 1998 until yearend 2014. Of the papers published earlier, the most often cited ones are included. A review of previous work is included in Jarrett [78].

2.3. Literature classification framework

The literature is thematically classified along the framework in Fig. 1. We identify four major research topics in the literature. Categories (1) to (3) comprise the supply chain that material follows before being used in hospitals. (1) Supply and procurement contains the literature regarding the purchasing of material as well as all activities related to the hospital-supplier interaction, for example outsourcing and means of supplier collaboration. Furthermore, the literature on demand forecasting is presented in this Section (2) Inventory management includes the literature on inventory policy, location planning, as well as classification schemes and practice-oriented inventory publications. Drug inventory management and drug shortages are also discussed. (3) Distribution and scheduling covers all material-linked distribution activities within and outside the hospital. In research topic (3), we focus on the actual transportation or distribution rather than the location of the goods as well as the handling of sterile medical devices. (4) Holistic supply chain management takes a holistic and mostly qualitative approach to optimize the supply chain.

All four research topics including their subtopics are presented and discussed. A focus is given to areas where quantitative methods are applied, however, for the sake of completeness and to provide insights on related research directions, the remaining research areas are also presented. The literature search yields 145 publications that are categorized along the presented framework. In case multiple categories are addressed, the publication is allocated to the most relevant category. Six methodological categories are distinguished. Optimization (containing an operations research (OR) model), simulation/scenario analysis, empirical research, literature review, theory/conceptual (introducing or discussing new theory or concept), case study (findings from practical research projects etc.).

3. Publication meta analyses

The subsequent section provides a quantitative assessment of the identified publications. Publications in this section are assessed from three perspectives: Thematically, methodically, and regionally. Thereafter, an overview is provided, and research opportunities are identified.

3.1. Thematic categorization

We generally limit the scope to publications published from 1998 onwards. However, eight earlier publications are included due to their pivotal importance for the relevant literature streams. A time-wise development of publications and its thematic scope along our review framework is provided in Fig. 2. The different shadings reflect the allocation to our four main categories.

The number of publications has grown considerably over time. The increasing relevance of hospital material logistics in academia is indicated by a nearly doubled number of publications from 2009 to 2011 until 2012 to 2014. The categories with the highest growth rates over the last years are (3) Distribution and scheduling and (2) Inventory management. Both categories combined account for an increase in publications from 14 between 2009 and 2011 to 34 between 2012 and 2014. In the entire time span, the majority of publications, 66 papers, has been published in (2) Inventory management.

3.2. Methodological categorization

The methodologies applied in the reviewed publications are presented in Fig. 3. In the chart, the color of the shapes indicates the quantitative nature of the applied methodologies. Over the entire time span, papers have most often been published in the field of case studies with 47 publications, and theory/conceptual with 32 publications. The category of optimization has experienced a large increase of publications from four in 2009 to 2011 to 15 in 2012 to 2014. This indicates a further evolving interest in the field of operations research on hospital materials management. The second quantitative-focused category, simulation/scenario analysis, also peaks in the last time segment, underlining the importance of quantitative research in hospital materials management.

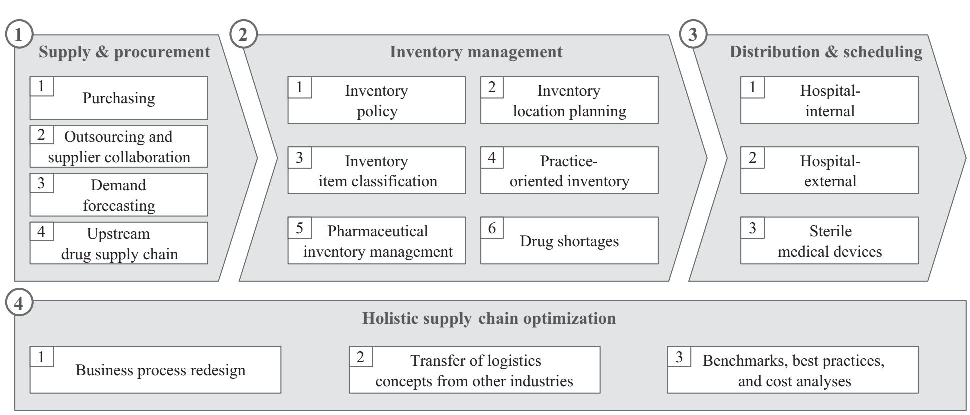

Fig. 1. Literature classification framework.

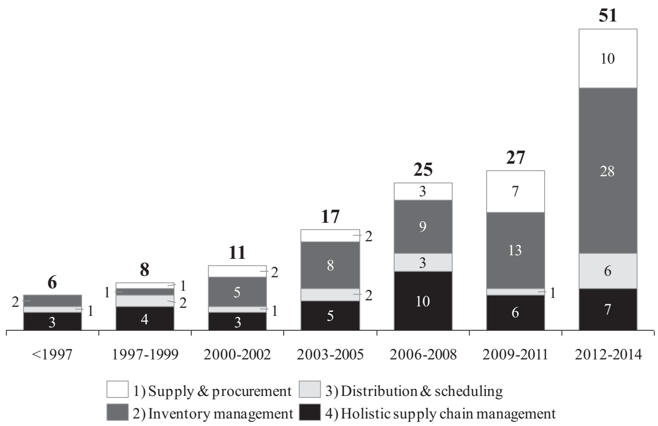

Fig. 2. Thematic categorization.

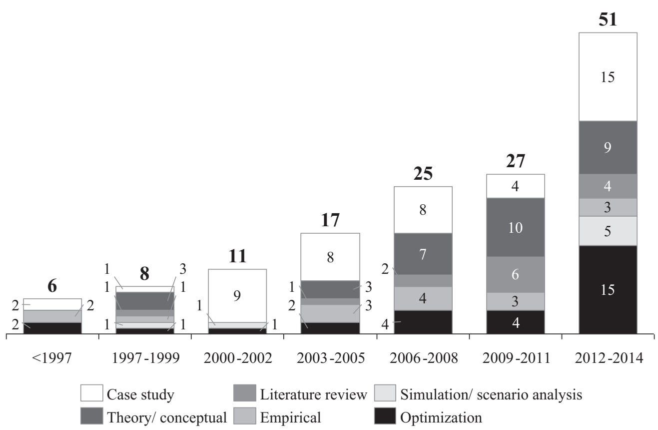

Fig. 3. Methodological categorization.

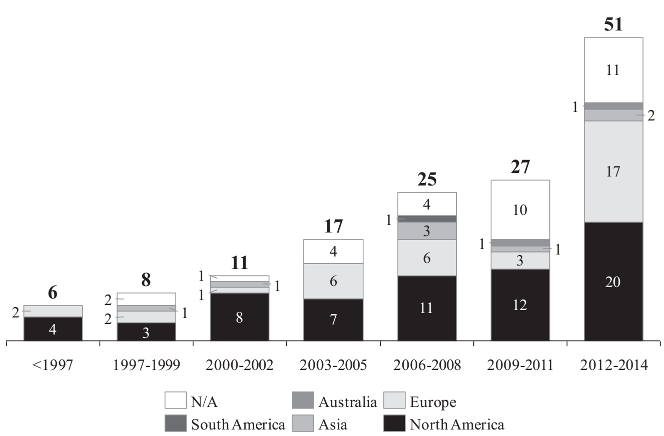

Fig. 4. Regional coverage of publications.

3.3. Regional categorization

In this section, the regional scope of the assessed publications is presented. This is to be understood as the place where research relates to, e.g., where the relevant case hospital is located. However, the location of the research institution is not relevant for this overview. Fig. 4 presents the regional scope for the entire time span. N/A indicates either publications that take a global scope, e.g., literature reviews, or methodology-focused publications, or that it was simply not possible to identify which locations the publications relate to. The filling indicates the regional allocation of publications. North America and Europe are the continents with the most publications during the entire time span with 65 articles and 37 articles respectively. Combined, this accounts for more than two thirds of total publications. Within North America, the U.S. account for 54 publications making it the country with most publications globally. Within Europe, the U.K. and the Netherlands lead with nine and six publications respectively. Due to the strongly regulated nature of national healthcare systems and their significant regional differences, it is of pivotal importance to perform research with a clear regional focus, considering specifics in national legislation. In our review, only English publications are considered, which might bring forward publications from English speaking countries and thus slightly bias the regional coverage display.

3.4. Overview of publications

A thematic and methodological overview of all publications is presented in Table 1. We derive that optimization techniques are mostly applied in (2) Inventory management and (3) Distribution and scheduling. Both research areas are characterized by rather well-defined problem settings that also occur in other industries, such as manufacturing. (1) Supply and procurement also offers possibilities to apply optimization techniques, but only five publications exist in this field of research. In (4) Holistic supply chain management however, no publications exist that apply optimization techniques. Potentially, this is due to the high complexity of integrated processes and the hard to define nature of holistic supply chain problems. Instead, mostly qualitative research is applied, namely theoretical/conceptual research or case studies. Another interesting insight is that most literature reviews are published within this field. This underlines that this publication fills a research gap as it focuses on publications applying quantitative techniques. A further evident research gap lies within the application of case studies and conceptual research in the field of (3) Distribution and scheduling.

4. Literature on topic: (1) Supply and procurement

A natural approach to minimize material costs is to minimize the actual purchasing costs. Supply chain costs constitute a major part of hospitals' operating expenses. For example, U.S. hospitals spent $27.7 bn. for drugs alone in 2009 [39]. Hospital material management literature mainly focuses on four areas. First, bundling of purchasing volumes and thus increasing purchasing power. In this stream of literature, hospital group purchasing organizations (GPOs) are chiefly discussed. Hospitals strive to increase their purchasing power against suppliers by combining their respective purchasing volumes. The second stream of literature primarily discusses hospital inventory outsourcing approaches, e.g., stockless inventory systems or vendor managed inventory (VMI), with regards to supplier integration. The third section offers an overview of demand forecasting, which is of high relevance for the hospital-supplier interface, while the last section sheds light on specifics of the upstream pharmaceutical supply chain and potential implications for hospital buyers. All four streams are presented below.

4.1. Purchasing

Hospitals are mostly organized in GPOs, i.e., voluntary alliances aggregating hospitals' purchasing volumes. In the U.S., 90% to 98% of hospitals are organized in purchasing alliances [24]. GPOs help to reduce material costs in a twofold manner. First, they allow leveraging economies of scale due to purchasing volume bundling. Second, they enhance price transparency and create price ceilings through framework contracts in which price bands are agreed on [24]. A qualitative comparison of advantages and disadvantages of GPOs is provided by Rego et al. [142] and Burns and Lee [24]. In line with the remainder of

Table 1
Overview of publications.

	(1) Supply and procurement	(2) Inventory management	(3) Distribution and scheduling	(4) Holistic supply chain management
Optimization	Hu and Schwarz [66] Iacocca [70] Rego et al. [142] Ross and Jayaraman [148] Zhao et al. [170]	Baboli et al. [9] Bijvank and Vis [21] Dellaert and van de Poel [37] Guerrero et al. [57] Kelle et al. [84] Little and Coughlan [103] Nicholson et al. [124] Priyan and Uthayakumar [140] Rosales et al. [146] Rosales et al. [147] Uthayakumar and Priyan [157] Vila-Parrish et al. [163]	Augusto and Xie [7] Bailey et al. [10] Banerjea-Brodeur et al. [11] Kergosien et al. [85] Lapierre and Ruiz [98] Medaglia et al. [116] Michelon et al. [119] Ozturk et al. [130] Shih and Chang [150] Swaminathan [153] Tlahig et al. [155] Van de Klundert et al. [90]	
Simulation/ scenario analysis	Azzi et al. [8]	Gebicki et al. [53] Pasin et al. [132]	Dean et al. [36] Di Mascolo and Gouin [107]	Iannone et al. [71] Iannone et al. [72]
Empirical	Burns and Lee [24] Nollet and Beaulieu [125] Oumlil and Williams [129] Kumar et al. [95]	Baumer et al. [12] Beier [13] De Vries [164] Fox and Tyler [51] Hall et al. [63] Huarng [67] Kaakeh et al. [82] Lee and Shim [101] McBride et al. [112]		Kafetzidakis and Mihiotis [83] Kim and Schniederjans [89] Zheng et al. [171]
Literature review	Jack and Powers [74]	Coustasse et al. [31] Irani et al. [73] James et al. [76] Fosso Wamba et al. [49]	Beliën et al. [14]	Abukhousa et al. [2] De Souza [151] De Vries and Huijsman [165] Ford and Scanlon [48] Jarrett [77] Jun et al. [81] Mazzocato et al. [111] Young et al. [168]
Theory/concept	Cruz and Marques [32] Brennan [23] Fein [43] van Donk [40]	Almarsdóttir and Traulsen [3] Alspach [5] Danas et al. [35] Fox et al. [50] Gu et al. [56] Gupta and Huang [59] Huys and Simoens [69] Johnson [80] Le et al. [100] Lee and Özer [102] Mangan and Powers [105] Mazer-Amirshahi et al. [110] McLaughlin et al. [114] McLaughlin et al. [115] Meiller et al. [118] Phillips and Berner [134] Rider et al. [143] Vaillancourt [158] Ventola [161]		Chandra [28] Di Martinelly et al. [106] Jarrett [78] Kim et al. [87] Kollberg et al. [91] Landry and Beaulieu [96] Meijboom et al. [117] Whitson [166] Young and McClean [169]
Case study	Bendavid et al. [16] Bendavid et al. [17] Bhakoo and Chan [19] Bhakoo et al. [20] Guimarães et al. [58] Haavik [61] Matopoulos and Michailidou [108] Mustaffa and Potter [121] Rivard-Royer et al. [144] Varghese et al. [159]	Abijith and Fosso Wamba [1] Beso et al. [18] Çakıcı et al. [25] Chan et al. [27] Chang et al. [29] Danas et al. [34] Fitzpatrick et al. [47] Franklin et al. [52] Granlund and Wiktorsson [54] Griffith et al. [55] Gupta et al. [60] Khurana et al. [86] Koppel et al. [92] Maviglia et al. [109]	Mühlich et al. [120]	A. Kumar et al. [94] Aptel and Pourjalali [6] Born and Marino [22] Coulson-Thomas [30] Dacosta-Claro [33] Fillingham [45] Ferretti et al. [44] Heinbuch [64] Jayaraman et al. [79] Kriegel et al. [93] Landry and Philippe [97] McKone-Sweet et al. [113] Pan and Pokharel [131] Trägårdh and Lindberg [156]

Table 1 (*continued*)

	(1) Supply and procurement	(2) Inventory management	(3) Distribution and scheduling	(4) Holistic supply chain management
		Novek [126] Patterson et al. [133] Piccinini et al. [135] Poley et al. [136] Poon et al. [137] Thomas et al. [154]		Venkateswaran et al. [160] Yasin et al. [167]

Table 2
Purchasing publications containing optimization models.

Publication	Problem description	Model characteristics	Objective function	Type of goods
Hu and Schwarz [66]	Role of GPOs in healthcare supply chain and cost reduction potential	Hotelling duopoly model	Minimize costs	Not specified
Rego et al. [142]	Decision support to set number of GPOs, size and composition for hospitals willing to cooperate	Metaheuristic (hybrid VNS/tabu-search)	Minimize hospitals' shared supply chain costs	Not specified
Ross and Jayaraman [148]	Purchasing strategy for bundled refurbished medical products	Mixed-integer problem solved with SA heuristic	Minimize total acquisition costs of purchasing plan	Durable items (new and refurbished)

this article, publications containing optimization models are displayed separately (see Table 2) and discussed in depth.

Rego et al. [142] present a decision support tool helping hospital purchasing managers to identify and to assess alternative GPO forms. For a defined group of hospitals willing to cooperate, the tool presents the number, size, and composition of GPOs and a financial assessment. A metaheuristic comprised of a two-module hybrid variable neighborhood search (VNS) and tabu search is applied to solve the optimization problem. The tool allows evaluating alternative cooperative purchasing strategies and is applicable for a wide range of purchasing groups. Ross and Jayaraman [148] focus on the single-hospital level. They assess how products should be bundled when placing orders at suppliers. They especially focus on bundling new products with refurbished products, which several U.S. healthcare providers have recently started to explore in order to reduce material costs. Examples for refurbished products constitute investment goods such as medical devices or electric beds, which are bundled with (new) consumable products. The authors develop a mixed-integer program (MIP) aiming to minimize the total purchasing costs. They build a heuristic based on simulated annealing (SA) to find near optimal purchasing strategies, i.e., which products to buy from which supplier and decide if to conduct a bundle or single item purchase. Potential item surplus in bundles exceeding the buyer's requirements are minimized in the objective function (apart from purchasing costs). Hu and Schwarz [66] assess the general role of GPOs in the healthcare supply chain and their impact on pricing mechanisms with a hotelling duopoly model. They find that GPOs indeed achieve lower prices for healthcare providers through increased competition between manufacturers. However, they carve out downsides of GPOs like reducing incentives for manufacturers to innovate and enhance their existing product portfolio.

Non optimization-focused publications include the following: Oumlil and Williams [129] discuss strategic purchasing alliances in the healthcare sector both in terms of organizational factors as well as personal factors. Organizational factors include, e.g., the hospitals' type and size while personal factors comprise, e.g., the education and the experience levels of purchasing managers. They find that selected demographic characteristics of purchasing managers are linked to decisions on alliances. For instance, job experience and the success of the alliance are related. Burns and Lee [24] provide an empirical study on the utilization, services, and performance of hospital purchasing alliances from the hospital material management's point of view. The authors find that purchasing alliances achieve cost reduction by lowering product purchasing prices, especially for commodity and pharmaceutical products. They stress that alliances further reduce transaction costs as contracts are commonly negotiated. However, cost benefit realization is hindered for service products or when physicians prefer certain items. Burns and Lee [24] further present several literature streams – not necessarily related to operations management – in the field of purchasing alliances, such as pooling alliances and value-chain alliances.

Another empirical study states that purchasing groups are subject to lifecycle stages [125]. The authors identify critical characteristics influencing the development of purchasing groups. These include payers' intervention, nature of benefits, procurement strategy, nature of relationships with suppliers, structure, and resources. They further develop a lifecycle model to show the evolution of GPOs and the changing importance of these characteristics.

Regarding future research opportunities in terms of methodology, Ross and Jayaraman [148] underline the combinatorial complexity of practical problems in healthcare logistics, marketing, and purchasing. They propose the development of heuristics in order to cope with large problem instances. Generally, there seems to exist a bias in this research stream towards manufacturing industries, thus healthcare in particular provides further research opportunities [129]. Other potential research fields include the assessment of performance determinants of GPOs to facilitate comparisons across purchasing alliance characteristics, e.g., in terms of size or management. Furthermore, such research would allow to identify the potential to differentiate between GPOs [24]. Also, assessing outsourcing activities compared to GPOs seems worthwhile for future research. Past publications indicate that the attractiveness of outsourcing logistics is positively correlated to hospital size [129].

4.2. Outsourcing and supplier collaboration

It is widely accepted that outsourcing logistics activities to third party providers can generate significant efficiency advantages for both parties due to economies of scale and scope, fixed cost reduction, and focus on core competencies [72,8]. There are many general studies on logistics outsourcing, but literature concerning healthcare is rather scarce, which is in line with the overall tendency in the healthcare sector to slowly embrace new SCM practices [113]. However, outsourcing inventory decisions to healthcare providers has recently gained importance, especially in practice where outsourcing concepts are widely applied [124]. Kim et al. [88] stresses the potential of VMI in the healthcare sector. The author finds that hospitals can significantly reduce inventory stock. However, he states that supply chain integration might be hindered due to the absence of standards for information sharing and missing participation of pharmaceutical manufacturers in collaborations.

In order to assess outsourcing opportunities, scenario modeling is applied in several publications. Azzi et al. [8] consider different outsourcing options for a healthcare network in central Italy, comprising several hospitals and one centralized logistics hub. The authors both qualitatively and quantitatively evaluate three scenarios with varying outsourcing degrees: Logistics self management, partial logistics outsourcing, and total logistics outsourcing. The qualitative assessment is mainly based on an extensive literature review while the quantitative assessment of outsourcing options is performed using a system dynamics simulation. The authors state that logistics outsourcing is often the most economical option for different sets of distribution network layouts. van Donk [40] develops a tool to assess several potential supply chain designs between a hospital and its supplier of medical and non-medical gases. Nicholson et al. [124] compare inventory costs of an in-house 3-echelon distribution network vs. an outsourced 2-echelon distribution network (i.e., direct delivery to the care unit) for non-critical medical items. For a detailed analysis of this paper, see Section 5.1.

There is a large stream of literature presenting and discussing case studies without quantitative methods or simulation/scenario analyses. One example that is thematically linked to the previously discussed publication is the work by Rivard-Royer et al. [144]. They present a case study in a Canadian hospital that applies a hybrid stockless inventory management system. Hybrid means that suppliers have two options to deliver to the hospital. Either they supply goods to the hospital's central warehouse, which is the classical approach, or the suppliers pack products according to the need of the respective care unit and perform direct delivery. The authors find that the hybrid model may yield marginal benefits compared to the classical approach. They also show that different forms of packing are a significant lever for cost savings. This packaging issue is analyzed in more detail in the publication by Kumar et al. [95]. The authors empirically assess whether package design plays a significant role in the hospitals' purchasing decision making process. They find that packaging and environmentally friendly supplies do currently not play a pivotal role in purchasing decisions in the U.S. Further case studies regarding VMI concepts in the hospital surrounding are presented in Bhakoo et al. [20], Guimarães et al. [58], Matopoulos and Michailidou [108], and Mustaffa and Potter [121]. All publications provide a good overview of the overall concept as well as its application in the hospital setting. Bhakoo et al. [20] state that VMI has widely been ignored in the healthcare industry. They qualitatively assess different collaborative arrangements between hospitals and pharmaceutical suppliers, such as the "ward box", a variant of VMI where hospitals place direct orders of the items required in a specific ward and the suppliers deliver to the ward without taking the detour of a central warehouse. They remarkably find that hospital material managers were more willing to undertake collaborative arrangements along the supply chain than their suppliers. Guimarães et al. [58] present an assessment of VMI regarding its benefits, risks, barriers, and enablers. They further conduct a case study of a multi-location hospital that aims to create transparency along its value chain. Matopoulos and Michailidou [108] study the application of CMI (co-managed-inventory), a form of VMI where hospitals remain partly responsible for inventory. The authors present a case study for a Greek hospital. Mustaffa and Potter [121] assess a private hospital in Malaysia and its supplier relations and identify two issues: Urgent orders and stock availability at the wholesaler. Based on their findings, they propose the introduction of a VMI setup in order to cope with these difficulties. Bhakoo and Chan [19] summarize complexity factors around pharmaceutical healthcare supply chains. They present factors that hinder the implementation of e-business processes in the procurement area of healthcare supply chains: Lack of consistency, poor data quality, and the global nature of supply.

Comparable to VMI approaches are consignment agreements in the hospital sector, where ownership of goods remains with the suppliers until they are consumed. This approach is mostly applied for expensive items, such as implants [41]. Compared to VMI approaches, recent literature on consignment agreements is rather scarce and focuses on case studies [16,17]. The authors present an RFID-based traceability system for consignment and high value products. Compared to other systems in the market, such as RFID-enabled cabinets or smart shelves, the system is rather simple and has lower technological requirements.

One obvious future research area is the extension of the outsourcing degree from VMI, where suppliers take over responsibility for hospitals' inventories, towards just-in-time (JIT). JIT means that suppliers provide goods to point-of-use locations in hospitals without intermediate buffer inventories. The implementation of JIT concepts in hospital supply seems to be hindered, however. Identifying underlying reasons and providing ideas on how to embrace those difficulties could be an interesting future research field. For a continued discussion on the general applicability of JIT, please refer to Section 7.2. Also, as mentioned before, the availability of information across the supply chain might hinder the applicability of more integrated supply chain concepts. Identifying how to increase data transparency, while respecting intellectual property rights and legal constraints, might bear future research opportunities. Another potential research area could be the application of optimization techniques in outsourcing. So far, optimization models have not been applied in this research field. Potential questions include determining the characteristics of products that could be outsourced or defining the optimal outsourcing degree, i.e., answering which product categories are appropriate for outsourcing.

4.3. Demand forecasting

One major obstacle for a better integration of hospitals and their suppliers is the unpredictable nature of hospital demand. It is argued by numerous researchers that the patient mix and the resulting demand for materials is very hard or impossible to predict [32,62,65,10,103]. However, as contracts with suppliers are occasionally building on minimum purchase quantities, accurate demand forecasting is of high relevance for hospital purchasing managers. Brennan [23] stresses the importance of regular demand forecasts based on clinical guidelines linking patient groupings' requirements with resulting materials demand. To tackle unreliable resource demand predictability, Varghese et al. [159] apply demand forecasting algorithms. Haavik [61] stresses the importance of sharing hospital demand information with suppliers, e.g., through implementing VMI software able to forecast demand and placing orders at suppliers accordingly. Danas et al. [34] cope with demand uncertainty through several point-of-use inventory locations to one large virtual inventory in an attempt to reduce demand uncertainty. For further reading, we refer to Jack and Powers [74], who provide a literature review on demand management and capacity management in healthcare services, and Narayana et al. [123], who investigate the redesign of the pharmaceuticals supply chain, not limited to hospitals. Improving forecasting mechanisms for hospital demand seems to bear worthwhile future research opportunities.

4.4. Upstream drug supply chain

In this section we offer a brief overview of changes in the upstream drug supply chain, i.e., the interface between drug manufacturers and wholesalers. We specifically point out one aspect that has an impact on hospital pharmacies.

Starting in the year 2005, the payment and distribution scheme of the U.S. pharmaceutical supply chain went through a significant transition. Drug manufacturers and wholesalers changed their collaboration model from Buy-and-Hold (BNH) to Fee-for-Service (FFS) [70]. In the BNH scheme, one of the wholesalers' major revenue sources was to speculate on drug price increases. When wholesalers held high stock levels and manufacturers increased their prices, wholesalers would hand down the higher price to their buyers, namely hospitals pharmacies. Apart from high stock levels, this scheme resulted in several other disadvantages, such as big fluctuations in wholesalers' order quantities, revenue losses for drug manufacturers, as well as unstable and unpredictable wholesaler revenues [170]. In the FFS scheme however, the wholesalers agree to reduce or eliminate the afore mentioned drug investment buying in return for fees paid by drug manufacturers to hold inventory and fulfill their distribution role [70]. According to Fein [43], the FFS scheme comes with two major threats for hospitals. First, the wholesalers' discount range is reduced as they share detailed order, inventory, and shipment data with drug manufacturers. This reduces their volume buying potential and consequently their discount range. Second, as inventory levels at wholesalers are reduced, the threat of drug shortages is significantly higher in the new scheme (see Section 5.6).

In this research area, two publications might be of interest for hospital pharmacy buyers. Zhao et al. [170] investigate the design and benefits of FFS contracts and derive implications for inventory policies and their parameters for drug manufacturers and wholesalers. Iacocca et al. [70] compare the differences of the two schemes and a third payment and distribution scheme, the Direct-to-Pharmacy (DTP) agreement, where wholesalers manage drug distribution and inventory for a fee, but the manufacturers remain the owner of the drug until it reaches the point-of-use [70]. As the focus of the presented publications lies mostly on the manufacturer-wholesaler interface, we believe that future research should focus on the explicit implications for hospital buyers.

5. Literature on topic: (2) Inventory management

While the management of inventory systems has been widely discussed in the industrial context, healthcare managers have traditionally paid little attention to the management of inventories [164,58,84,124,149]. However, in recent years, the management of inventory has been identified as one key lever to realize efficiency improvements without negatively affecting the care of patients. Scholars estimate that 10% to 18% of hospitals' net revenues are spent on inventory costs [78,124]. Hospitals in the U.S. and in France hold an average amount of USD 4,000 and USD 5,720 per bed in medical supplies alone, respectively [6].

In hospitals, goods distribution is typically designed as a multi-echelon inventory system. A central warehouse receives goods from suppliers. Commonly, the central warehouse is closely connected to the central pharmacy being in charge of pharmaceuticals handling and the production of perishable drugs, e.g., intravenous fluids. The central warehouse regularly delivers to the point-of-use inventories that are typically located close to patient care locations (see Fig. 5; similar figures may be found in Bijvank and Vis [21]; Rivard-Royer et al. [144]). Apart from this "traditional method", two other goods distribution systems are typically applied in practice, i.e., "semi-direct delivery", where the suppliers skip the central warehouse and deliver directly to the point-of-use location. The third approach, "direct delivery", is closest to JIT meaning that the supplier takes responsibility for reacting to patient demand and refilling supplies at the point-of-use locations [6]. Scholars distinguish between the hospital-external and hospital-internal supply chain. While external supply chain integration efforts receive most of the attention from the area of SCM, the internal supply chain remains the weak spot of the entire chain [97].

Regarding the setup of hospital inventory systems, several studies argue that hospital inventory management is to some extent comparable to other industries. Thus, proven concepts can be transferred to the healthcare industry. Due to the storage space constraints at the point of delivery, i.e., the care unit, laboratory, or the operating theater, Little and Coughlan [103] argue that the respective inventories are comparable to retail. Another retail inventory management aspect that could be incorporated in the healthcare environment is the application of "actual use inventory management", meaning the use of point-of-use data in the upstream supply chain [159]. Danas et al. [35] see strong similarities with the case of spare part inventories for production machines in industrial plants. Decision makers are faced by a trade-off between the costs for production delays and the costs for safety stock. Literature on hospital inventory management is presented in the following section. The discussion starts with the most relevant field of literature, which is "inventory policy". Thereafter, publications in "inventory location planning", "inventory item classification", and "practice-oriented inventory" are discussed. Afterwards, we present specifics of and additional requirements in the management of drugs in "pharmaceutical inventory management". The chapter concludes with a section

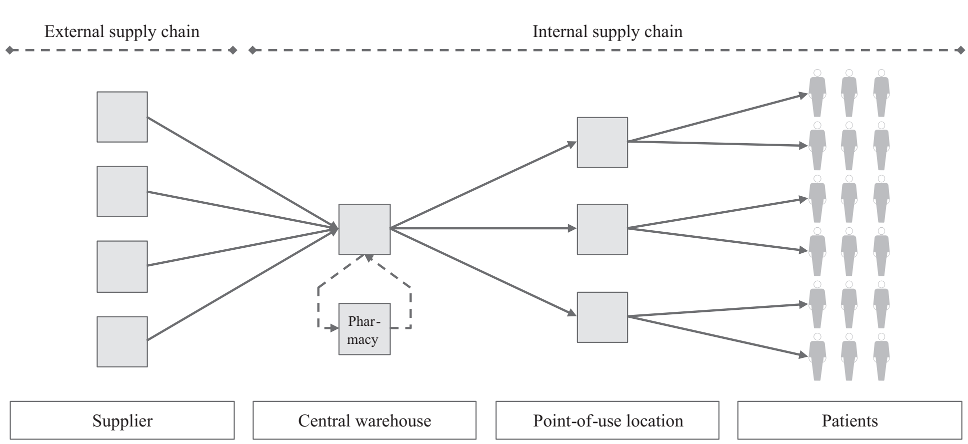

Fig. 5. Illustrative supply chain.

focusing on drug shortages and strategies on how to avoid them. Future research directions are provided at the end of each section.

5.1. Inventory policy

The following section presents the literature regarding inventory policy. The most widely discussed topic is the choice of the suitable inventory policy, which comprises the definition of the inventory review cycle (periodic or continuous) and parameter setting for the reorder point, the reorder quantity, and/or the order-up-to level. All presented publications include optimization models. Aspects of hospital inventory management literature reviews may further be found in the following publications. Bijvank and Vis [21] frame their problem with a brief review of replenishment policies for hospital inventory systems, de Vries [164] gives an overall introduction into inventory management, and Rosales et al. [146,147] introduce their research with a general review of inventory models and briefly discuss related quantitative models in the hospital setting.

The section starts with an overarching discussion of the inventory review logic. Thereafter, the publications are clustered along the inventory locations that they address. It starts with "multi-echelon", followed by the "central inventory". Then, the focus shifts towards the patient, meaning the "point-of-use location". At the end of the section, future research opportunities are presented.

5.1.1. Inventory review logic

As the notation in the literature varies, we introduce the following notation in order to make policies comparable: T (Review cycle time), s (reorder point), Q (order quantity), S (order-up-to level), c (can-order point). An overview of the basic inventory policies is provided in Fig. 6. We distinguish between periodic review and continuous review. Periodic review comprises the *(T, S)* policy, which is also called "par level policy". It means that after every review cycle T, orders are triggered so that the order-up-to level S would be on stock. Continuous review comprises two basic policies. The first policy is the *(s, Q)* policy, where whenever inventory levels fall under reorder point s, a refill quantity of Q is triggered. The second continuous policy is the *(s, S)* policy, where instead of a fixed reorder quantity Q, orders are triggered so that the order-up-to level S would be on stock, as soon as storage falls below reorder point s. *N/A* indicates that the policy framework is not applicable. A performance comparison of periodic fixed order size replenishment policies and order-up-to policies is provided in Bijvank and Vis [21]. Regarding stock, we distinguish between safety stock being the average buffer inventory, and the cycle stock being the average inventory above the safety stock [84].

Relevant literature containing optimization models is presented in Table 3. Most publications apply a periodic inventory review policy, which is in line with historic and current practice in hospitals, especially at point-of-use inventory locations such as the wards [124]. In light of the ongoing modernization of point-of-use technologies like the introduction of advanced identification technologies as barcodes

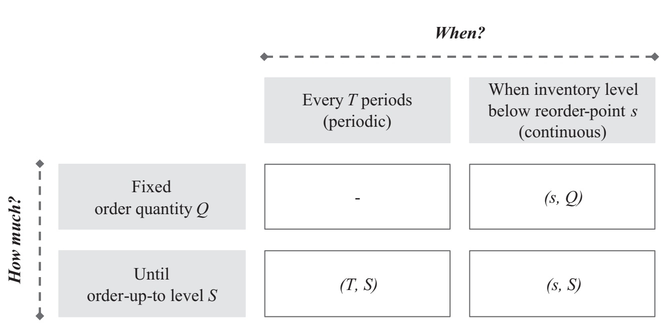

Fig. 6. General inventory policies.

or radio-frequency identification (RFID), researchers have recently started investigating new types of replenishment policies, e.g., hybrid policies [21,145,146]. Rosales et al. [146] develop such a hybrid replenishment policy. They generally perform a cost-efficient periodic review. However, in order to avoid costly stock-outs, continuous review is allowed. While PhD theses are out of scope for this review, due to its importance we refer to Rosales [145] who elaborates on technology-enabled new inventory policies for hospitals. Kelle et al. [84] study an automated ordering system, which allows for a continuous review. Uthayakumar and Priyan [157] argue that periodic inventory review policies are not applicable in practical healthcare settings due to the uncertainty of patient arrivals and resulting demand. Most of the discussed publications incorporate capacity constraints in their inventory models, as in the hospital setting, space is a limiting factor, especially at the point-of-use inventories.

When implementing the defined inventory parameters in practice, some typical obstacles exist. Inventory par levels often reflect the desired inventory levels of physicians and nurses rather than the calculated inventory levels. Thus, par levels tend to be experience- or policy-driven rather than data-driven [139]. Furthermore, it appears to be common to keep "hidden" safety stock in several locations at care units due to difficulties in policy implementation, personal judgment, and silo-structured organizations [58].

5.1.2. Multi-echelon inventory

In the following publications, supplier inventories are discussed parallel to hospital inventories. Baboli et al. [9] provide a cost comparison for a joint optimization of a pharmaceutical supply chain from a retailer and hospital perspective. They take into account inventory and transportation costs and consider two cases where costs are optimized, i.e., a decentralized and a centralized case. In the decentralized case, companies independently optimize their costs, while in the centralized case, several participants of the supply chain are considered as a single organization. They focus on products with high demand and assume that demand for the respective products is deterministic. Uthayakumar and Priyan [157] take an entire value chain perspective in the case of pharmaceuticals. In their inventory model, they include production and distribution of pharmaceuticals. They develop an algorithm to find the optimal inventory lot size, lead time, and number of deliveries with minimum costs under a continuous review policy. The algorithm is based on a Lagrangian multiplier approach. In a second work, Priyan and Uthayakumar [140] extend their model to cover a fuzzy-stochastic environment, discrepancies between ordered quantities and actually received quantities, and lead times consisting of mutually independent components. Based on the signed distance method, the environment is defuzzied and an optimal inventory policy is determined using the same Lagrangian multiplier approach as in the first paper. Nicholson et al. [124] assess the differences between an in-house 3-echelon inventory system and an outsourced 2-echelon distribution network, where the replenishment activities are performed by an outside agent that directly delivers to the point-of-use inventory locations in the hospital. The authors develop two optimization models to minimize the holding and backorder costs and apply a heuristic to solve their problems. They find that outsourcing the distribution of non-critical items is a viable choice, enabling staff to concentrate on patient care activities.

Guerrero et al. [57] develop a methodology to find near-optimal inventory policies for multi-echelon inventory networks, i.e., one central inventory and n point-of-use inventories. They aim to minimize the total stock on hand for the entire system and employ a Markov decision process. The reorder points at both echelons are derived via a probability calculation while the optimal order-up-to level is one unit higher than the reorder point at the point-of-use inventories. The near optimal order-up-to level at the central inventory is derived from a heuristic algorithm. Their approach is

Table 3
Inventory policy publications containing optimization models.

Publication	Problem description	Model characteristics	Objective function	Type of goods	Review logic	Replenishment policy	Capacity const.	No. of products	Invent. type
Baboli et al. [9]	Cost comparison of 2-level pharmaceutical supply chain: Decentralized vs. centralized replenishment	Heuristic	Minimize total cost	Pharmaceut.	N/A	N/A	Yes	Multi	Multi echelon
Bijvank and Vis [21]	Inventory policy (reorder points and order quantities) for point-of-use inventories	Heuristic	(1) Maximize service level (2) Minimize required capacity	Disposable items	Periodic	(T, S)	Yes	Multi	Point-of-use
Dellaert and van de Poel [37]	Easily applicable inventory policy for central inventory	Heuristic	Minimize ordering cost per cycle	Consumable items	Periodic	(T, s, c, S)	No	Mulri	Central inven-tory
Guerrero et al. [57]	Optimal inventory parameters for mutli-echelon inventory	Heuristic based on Markov DP	Minimize stock on hand of entire system (CU and CP)	Non-critical, e.g., infusion solutions	Periodic	(T, S)	Yes	Multi	Multi echelon
Kelle et al. [84]	Easily applicable algorithm for inventory policy parameter setting in point-of-use inventory	Heuristic	(1) Minimize ordering and inventory cost (2) Minimize number of refills	Pharmaceut.	Contin.	(s, S)	Yes	Multi	Point-of-use
Little and Coughlan [103]	Optimal stock levels under hospital space constraints	Heuristic (constraint programming)	(1) Maximize minimum service levels (2) Max. average service levels	Sterile items, consumables	Periodic	(T, S)	Yes	Multi	Point-of-use
Nicholson et al. [124]	Costs and service level comparison for in-house 3-echelon inventory vs. outsourced 2-echelon distribution network	Heuristic (greedy-algorithm)	Minimize inventory cost (holding and backorder)	Non-critical inventory items	Periodic	(T, S)	No	Single	Multi echelon
Priyan and Uthayakumar [140]	Extension of Uthayakumar and Priyan [157]: Fuzzyness, delivery quantity discrepancies, independent lead times	Fuzzy model defuzzied w. signed distance method	Minimize total cost	Pharmaceut.	Contin.	(s, Q)	Yes	Multi	Multi echelon
Rosales et al. [146]	Hybrid inventory policy (periodic and continuous review) and inventory parameter definition	Heuristic based on simulation	Minimize long-run average cost per unit time	Pharmaceut., medical supplies	Periodic, continu-ous	(T, S, s, Q)	Yes	Single	Point-of-use
Rosales et al. [147]	2-bin replenishment system: (1) Parameter optimization for periodic review (2) RFID use to enable continuous review	SMDP, linear programming	Minimize order cost and stockout cost	High volume, low cost items	Periodic, continu-ous	N/A	Yes	Multi	Point-of-use
Uthayakumar and Priyan [157]	Optimal inventory lot size, lead times and number of deliveries for hospital delivery	Langrangian multiplier algorithm	Minimize total cost	Pharmaceut.	Contin.	(s, Q)	Yes	Multi	Multi echelon
Vila-Parrish et al. [163]	Inventory and production policy for pharmaceuticals with 2 stages: Raw material and highly-perishable finished good	Heuristic based on Markov decision process	Minimize expected inventory and production cost	Perishable pharmaceut., e.g., intrav.	Periodic	(T, S)	No	Single	Central inven-tory

especially suitable for non-critical goods, such as infusion solutions. In summary, publications cover inventory parameter setting as well as cost comparisons within and outside the hospital.

5.1.3. Central inventory

Dellaert and van de Poel [37] develop a simple and easily applicable inventory control rule for the hospital's central warehouse. The new policy called "*(R, s, c, S)* policy" is in our notation a *(T, s, c, S)* policy, which is an extension of the *(T, S)* policy that incorporates a can-order level *c*. Whenever inventory levels fall below *c* at the review, an order up to level *S* can be triggered, while when inventory levels fall under *s*, an order must be triggered. For a periodic review with given review cycles, the inventory parameters are determined using a simple algorithm that minimizes ordering costs based on order bundling. A special case regarding the management of the central inventory is studied by Vila-Parrish et al. [163]. They discuss inpatient medication with two stages being raw materials and finished goods. This holds for example for intravenous fluids that are produced in the hospital pharmacy. All goods are perishable, but finished goods are of a more perishable nature. The authors model production and raw material ordering using a Markov decision process.

5.1.4. Point-of-use location

In this section, the inventory closest to the patient, being the point-of-use location, is discussed. Bijvank and Vis [21] determine the optimal inventory policy for hospital point-of-use inventories. The authors develop two exact models: A capacity model and a service model. In the capacity model, they maximize the service level subject to capacity restrictions while in the service model the strategy is vice versa. They develop a simple heuristic inventory rule that can be easily utilized by hospital staff for the capacity model. Little and Coughlan [103] provide a constraint programming based algorithm that finds optimal inventory parameters, which are service level, delivery frequency, and order-up-to amount for a periodic inventory policy (*T, S*). They especially stress space restrictions and criticality of items.

The 2-bin replenishment system, a special replenishment system used in practice, applies two equally-sized bins in the care units, i.e., one bin where goods are taken from and one reserve bin. Once one bin is empty, replenishment is triggered, mostly relying on Kanban logic. This system is discussed in the following publications. Rosales et al. [147] study the 2-bin replenishment inventory system in combination with RFID tags and assess the applicability of different replenishment policies. Generally, a periodic replenishment policy is applied. Rosales et al. [147] assess two ways of optimizing the 2-bin replenishment system: Through parameter optimization for periodic review and through replenishment policy optimization shifting to a continuous replenishment policy. For parameter optimization, the periodic replenishment policy is modeled and it is demonstrated that the average costs per unit time is quasi-convex, thus allowing for a simple search to find the optimal review cycle. The policy change-driven optimization is enabled through the incorporation of RFID tags, allowing for continuous replenishment. Using a semi-Markov decision model (SMDP), the optimal replenishment policy is modeled and heuristically determined. Landry and Beaulieu [96] extensively discuss the 2-bin replenishment inventory system and assess which lean concepts it addresses.

Automated inventory systems at the point-of-use are discussed by the following two publications. Kelle et al. [84] provide the reorder point *s* and order-up-to level *S* for the point-of-use inventory of an automated ordering system in a continuous review setting. These inventory parameters are derived via a near-optimal allocation policy of safety stock and cycle stock. Parameters are derived using an iterative heuristic algorithm. Rosales et al. [146] develop a hybrid inventory policy for point-of-use hospital inventories, called "(*s, S, R, Q*) policy". They combine a periodic (*T, S*) policy with a continuous (*s, Q*) policy. Consequently, in our notation this equals a *(T, S, s, Q)* policy. During the review cycles, reactive replenishments are allowed. This new policy is especially applicable for automated dispense machines (ADMs) at point-of-use inventory locations. The authors develop a simulation-based heuristic to determine the parameter values for the reorder points, the order-up-to level, the order quantity, and the review cycle. They find that hybrid policies may provide substantial cost benefits versus purely periodic or purely continuous reviews.

Although a multitude of publications in the field of hospital inventory policy exists, this area remains promising for future research. Potential research includes the unpredictable nature of demand in hospitals and its implications on inventory policies. A majority of the presented publications focus on goods with high turnover and predictable demand. However, demand with low volume and lumpy characteristics and its potential effects on workload and policy setting is hardly considered. This area of research is stressed by Kelle et al. [84] and Little and Coughlan [103]. Furthermore, most papers assume independence of the demand for the different goods [124,84]. Including dependencies into inventory models could be an interesting research field. Regarding the characteristics of inventory items, it could also be beneficial to incorporate expiration dates or special storage requirements such as cooling [57]. Further, the effects of substitution products on service levels in case of stock-outs could be assessed, as proposed by Bijvank and Vis [21], or the fact that emergency deliveries from other care units are possible and for many goods occur at little cost. For multi-echelon inventory settings, a further research area could be to incorporate lead times into inventory models, especially between outside suppliers and the hospital, as proposed by Nicholson et al. [124]. A detailed assessment of review cycle length at the point-of-use inventories and lead times of respective suppliers could therefore be beneficial [21]. Stressing the hospitals' need for simplicity and ease of usage could also be a potential future research area. Typically, staff dealing with logistics activities in hospitals often does not have the same technical background and knowledge as their counterparts in manufacturing industries. Consequently, the implementation of sophisticated inventory systems may be difficult in hospitals. Examples where the usage could be eased comprise simple inventory policies for large-scale inventory systems (e.g., [146]) or materials handling of ADMs.

5.2. Inventory location planning

Danas et al. [34] provide a publication related to inventory layout planning. The authors introduce the concept of a virtual hospital pharmacy that bundles the inventories of several hospitals in one specific geographic region to allow for a more efficient use of storage capacity. Pasin et al. [132] assess the impact of inventory pooling by using a simulation tool. They show that significant efficiency improvements are possible when centralizing inventories of several hospitals. Thomas et al. [154] assess placing an ADM in the point-of-use inventory at an operating room. The authors show that benefits can be realized through the reduction of preparation and setup time of medication. For emergency medications, the preparation and setup time could be reduced from fifteen to five minutes.

In the context of manufacturing industries, strategic planning of inventories like inventory location or layout planning is a large research area. Apart from defining inventory locations, the question where goods should be stored in a multi-echelon inventory setting has been addressed [26]. However, in the healthcare context, inventory location or layout planning is a rather untouched research field. One potential justification is that in the process of designing a hospital, planners focus on medical aspects, such as the location of operating theaters and wards. Logistics planning is often performed at a late stage, which leads to immature solutions that are not optimal from a materials management perspective

[33]. Future research opportunities could lie in the development of an integrated approach for hospital layout planning that better incorporates logistics aspects on the strategic level.

5.3. Inventory item classification

One lever to efficiently manage inventory is to categorize inventory items and establish individual inventory policies for these categories. This allows for standardized treatment of items within the same category, e.g., in terms of safety stock levels, required management attention, purchasing strategies, etc. In a case study by Beier [13], 45% of U.S. hospital pharmacies were using a classification scheme to distinguish important items. Potential categorization methods include ABC analyses, meaning categorization along the items' monetary value and rate of consumption, and VED (vital, essential, and desirable) analyses, which is a classification scheme along criticality of items or combinations of the above. Khurana et al. [86] develop a combination of ABC and VED classifications in order to define the required management attention for the different item categories. A case study for a combined ABC/ VED classification is provided by Gupta et al. [60]. Danas et al. [35] transfer the MASTA logic (multi attribute spare tree analysis), a concept that has been developed in the context of industrial spare parts, to the hospital inventory case. The idea is to classify each drug item along a classification tree in order to determine its stock and inventory strategy, thus to ascertain whether the respective drug needs a safety stock within the respective clinic, hospital, or geographic region, or if it can be supplied as a JIT item. Classification is performed along four dimensions: Patient treatment criticality, supply characteristics, inventory problems, and usage rate. We further refer to Al-Qatawneh and Hafeez [4] who present a multi-criteria inventory classification based on criticality, cost, and usage value, knowing that conference proceedings are not in scope of this review (see Section 2). Gebicki et al. [53] incorporate drug characteristics into inventory policy. They achieve higher patient safety and lower overall costs compared to traditional inventory management approaches. They evaluate the performance of several inventory policies with regards to total costs and service levels using event-driven simulation. The policies differ in the levels to which they incorporate information about the drugs, such as criticality or availability, cost components, e.g., whether stock-out or waste costs are included, as well as the application of sophisticated techniques, e.g., conditional demand forecasting.

Future research potential lies in the extension of the previously presented models in order to assess correlations between drug characteristics and the applied policy versus stock-out costs and the individual cost components [53]. Inventory item classification is further required for the use of innovative inventory systems, such as virtual pharmacies.

5.4. Practice-oriented inventory

Several practical case studies and empirical publications on inventory management exist. Huarng [67] assesses material management practices in Taiwan across several hospitals in an empirical study. Across the participating hospitals, purchasing strategies, inventory turnover rates, and inventory fill rates are compared across the participating hospitals, and significant performance disparities are worked out. An exploratory case study performed by de Vries [164] underlines the complexity of inventory management in hospitals. The author identifies and assesses the relevant stakeholders and their interests in the process of redesigning a hospital inventory system. Beier [13] assesses inventory policies from a U.S. data sample and identifies cost improvement potential in inventory management and the collaboration with suppliers. Poley et al. [136] present a case hospital which contains two pharmacy inventory and distribution systems, i.e., a multi-echelon system and a ready-to-use distribution system. Both systems are systematically compared and differences in their cost structures are highlighted.

Future practical research on inventory management should be performed in order to better understand the concrete differences between industrial settings and hospitals. Furthermore, reports on past inventory projects in hospitals would be highly beneficial in order to understand the dynamics and potential obstacles in the hospital setting [164].

5.5. Pharmaceutical inventory management

Pharmaceuticals impose high requirements on inventory management. According to Almarsdóttir and Traulsen [3], inventory management for pharmaceuticals differs from other medical product categories based on their specific characteristics. While hospital inventory-related publications on pharmaceuticals were already discussed in detail earlier, we refer to Kelle et al. [84], Priyan and Uthayakumar [140] and Uthayakumar and Priyan [157], who evaluate pharmaceutical supply chain specifics from the hospital's perspective. For a general introduction to hospital inventory management for pharmaceuticals, we refer to Vila-Parrish and Ivy [162]. Based on regulatory constraints, hospitals must make sure that information about the manufacturer, production lots and/or dates, as well as shipping information, etc. must be registered and known [25]. In order to fulfill these identification requirements and prevent medication errors and costly return deliveries, hospitals rely on identification means, namely barcodes and RFID. In the following section, both technologies and their application in hospitals are presented. The section concludes with a brief overview of drug handling techniques.

The use of barcodes is the today's most widespread identification technology. According to a cost-benefit analysis by Maviglia et al. [109], hospitals can achieve significant savings when applying a barcode-based identification/dispensing system instead of a manual system. In their specific case, the break-even point for the upfront investment occurred within one year after the implementation of the new system. Poon et al. [137] find that by implementing a bar code based hospital pharmacy system, the rate of dispensing errors can be significantly reduced. Pitfalls of such a system are presented by Phillips and Berner [134]. The work by Koppel et al. [92] concentrates on workarounds that are performed by medical staff when barcode medication administration systems (BCMA) are in use. Another work by Patterson et al. [133] presents a case study on implementation problems when using BCMA. The second and more technologically sophisticated identification technology is RFID. Key advantages include easier scanning and a high product visibility along the supply chain, however at a high implementation cost. A general introduction to the supply chain implications of using RFID – not limited to healthcare – is provided by Lee and Özer [102] and Irani et al. [73]. For RFID applications in the healthcare industry, we refer to Coustasse et al. [31] and Fosso Wamba et al. [49], who provide comprehensive literature reviews. The former find that despite the rising penetration of RFID in healthcare, few empirical studies exist that assess the actual potential of RFID. An exception is the work by Abijith and Fosso Wamba [1], who assess the financial impact of RFID-enabled transformation projects in the healthcare sector. Lee and Shim [101] investigate on the rationale behind introducing RFID in the healthcare industry. A highly practice-relevant work is provided by Chang et al. [29], who elaborate on where to mount RFID tags on products from a material handling perspective. Potential future use cases for the information generated through the application of RFID are presented by Meiller et al. [118] to further optimize material handling and reduce safety stock levels. A comparison of barcodes and RFID is provided by Çakici et al. [25] and Chan et al. [27]. Regarding inventory policies, Çakici et al. [25] find that continuous review is superior to periodic review whenever real-time information are available, which is the case for RFID-enabled inventories.

Regarding pharmaceuticals inventory design and drug distribution, hospitals employ either a classical ward stock system or a unit dose drug inventory and distribution system. In the classical system, inventory is held at the wards and can be divided into standard- and patient-specific medication. In a unit dose system, drugs are being picked in the central pharmacy according to the patients' actual needs [135]. New material handling technologies are commonly first adopted in the central hospital pharmacy, where manual picking is replaced by ADMs. There are case studies at hand regarding their effects and learning from their implementation: In particular, the publications by Fitzpatrick et al. [47], Franklin et al. [52], and Piccinini et al. [135] evaluate ADMs in hospital pharmacies. Major effects include a significant reduction of dispensing errors, reduced picking times, increased staff satisfaction, and better use of storage capacity [47,52]. Piccinini et al. [135] present and analyze an automated picking workstation as part of an automated pharmacy distribution center for a group of hospitals. They focus on the actual picking step and assess how to pick very diverse and complex objects available on belts or bins. Novek [126] and Granlund and Wiktorsson [54] more broadly assess the implementation and implications of automation in hospital-internal logistics. For a literature review on types and causes of dispensing errors, we refer to Beso et al. [18] and James et al. [76]. Future research should further incorporate new handling technologies that emerge in other industries with a focus on their applicability in hospitals.

5.6. Drug shortages

In recent years, drug shortages have occurred more and more often, having notable implications for hospital material management in general and inventory management in particular. Historically, the problem of drug shortages has mostly been common in either niche drug segments or developing countries. However, since the early 2000s, it has been reported that several drug groups in the U.S. are insufficiently supplied – a trend which experts argue is also prevalent in Europe, while exact data to prove this is missing [51,69,100].

Most of the existent literature focuses on drug shortages in the U.S. A variety of publications assesses the causes for drug shortages and their implications to the healthcare system. Reasons for shortages include the unavailability of raw material, production ramp-downs or manufacturing difficulties, mergers and acquisitions of drug manufacturers, voluntary recalls, regulatory issues, unexpected demand, natural disasters, and labor disruptions [56,105,161]. Drug shortages have significant negative financial effects for the healthcare system as well as the quality of patient care [5,12,82]. Nowadays, pharmacists and pharmacy technicians spend an average of 8-9 hours per week on drug shortage related activities [82].

Several authors present very hands-on suggestions on how to cope with drug shortages from a hospital logistics perspective. One key factor is to take proactive action, which includes purchasing strategies as well as the implementation of concrete actions plans that ought to be developed before shortages occur. The plans include lists of substitute products and hospital organizational issues, such as to define responsibilities in case shortages occur. Introducing substitute products might have significant effects on logistics processes. For example, the IT and inventory systems must be able to cope with short-term changes of drug names etc. [110]. In inventory management, one lever to cope with drug shortages is changing the inventory policy and updating the order point and order quantities. Also, inventory sharing and pooling, as well as rationing and prioritizing policies should be considered [80]. Having transparency on upcoming or expected shortages and the actual inventory level of respective drugs helps to be able to act proactively [80].

Apart from the rather practical action plans discussed in the previous publications, there are also publications that present general guidelines on how to attune to (potential) drug shortages [50,59,114,143,158]. We also refer to a number of studies that focus on the effects of shortages for certain drug groups [55,63,112,115]. According to pharmacists, there exists a lack of information needed when managing shortages, e.g., actual inventory data throughout the hospital [82]. Consequently, one future research area could be to further enhance data transparency and the availability of up-to-date stock information.

6. Literature on topic: (3) Distribution and scheduling

The subsequent section discusses hospital-internal and hospital-external distribution and scheduling topics. Due to its distinct characteristics, the logistics of sterile items is presented in a third category. Hospital-internal distribution comprises mainly routing and scheduling problems of goods within the hospital, primarily from the central warehouse location to the respective care units. External distribution relates to inter-hospital transports as well as waste management. Sterile items handling comprises both transportation tasks as well as the actual sterilization process.

6.1. Hospital-internal distribution and scheduling

In the field of hospital-internal distribution and scheduling, four publications that contain optimization models are identified (see Table 4). "Classical" pharmacy delivery is scarcely addressed in the literature [7]. However, rather specific issues are discussed, such as routing and scheduling problems of combined storage/delivery material management systems, e.g., mobile medicine delivery closets. Interestingly, due to the different delivery tools and setups, standards and common practice on how to transport material in hospitals hardly exist.

Augusto and Xie [7] and Michelon et al. [119] explore delivery problems of sophisticated inventory storage and delivery systems, i.e., medicine closets and twin trolleys. Augusto and Xie [7] consider a hospital pharmacy delivery problem. In their study, pharmacy delivery is performed in a manner such that care units are equipped with mobile medicine closets. Periodically, these closets are collected and transported to the central pharmacy for inventory stock assessment and refill. The problem consists in creating a transportation and supply plan. The aim is to have a balanced workload for the two limiting human resource types, i.e., transporters and pharmacy assistants. The problem is formulated as a MIP and a near optimal schedule is determined using a standard solver. In a second step, a simulation model is applied to redesign the pharmacy delivery process in a case study. Michelon et al. [119] compare two supply distribution systems. In their research case, supplies are delivered in a twofold way: Either through so called "twin trolleys" that contain most of the regularly required supplies, which are always doubled. One trolley is in use at the point-of-use and the "twin" is located at the central inventory location. Moreover, there are "non-twin trolleys" containing non-medical items, e.g., meals or cleaning products. Each of those trolleys is assigned to a number of point-of-use locations. In their publication, Michelon et al. [119] assess whether it is beneficial to change the allocation of items to the twin or non-twin trolleys relying on a tabu search heuristic.

Linen delivery is modeled and optimized by Banerjea-Brodeur et al. [11]. Based on shortfalls that regularly make emergency deliveries to the care units necessary, the transportation system is reviewed. The authors set up a periodic vehicle routing problem (VRP) in order to optimize delivery routing, scheduling, and quantities. To solve the VRP, a tabu search heuristic is applied.

Table 4
Hospital-internal distribution and scheduling publications containing optimization models.

Publication	Problem description	Model characteristics	Objective function	Type of goods
Augusto and Xie [7]	Transportation and supply plan for mobile medicine closets located at care units; weekly replenishment in central pharmacy	Mixed-integer linear programming, simulation	(1) Minimize number of routes (2) Minimize workload	Pharmaceut.
Banerjea-Brodeur et al. [11]	Deliver quantity and schedule of regular linen delivery from central laundry to care units	PVRP solved with tabu search heuristic	Minimize total cost	Laundry (linen)
Lapierre and Ruiz [98]	Multi-item inventory replenishment schedule under storage and manpower capacity constraints	Mixed-integer non-linear prob., meta-heuristic search	Minimize total inventory cost and minimize deviation of workload equilibrium	Not specified
Michelon et al. [119]	Comparison of mobile inventory and distribution systems with varying amount of items kept locally in care units	Tabu search heuristic	Minimize number of tasks that cannot be performed by respective system	Medical, bed-related, meals, etc.

Dean et al. [36] focus on scheduling pharmacists who visit care units in order to trigger medication orders. In their model, drug prescriptions are added to the patient files, which are typically mounted to the bed of the respective patient. The study demonstrates that changing the time of the day when the visit is performed affects the delay of medication arrivals.

The publication by Lapierre and Ruiz [98] assesses scheduling activities and logistics optimization. The authors state that in the context of hospital supply systems, basically two approaches exist to plan logistics activities. First, the inventory-oriented approach where in multi-echelon inventory settings, orders are placed whenever reorder points are met. In this predominant approach in the literature, the main focus lies on assuring sufficient stock levels (see Section 5). According to the authors, this approach however neglects further questions such as planning of scheduling activities and human resources. Questions to be answered include: When should employees work? How often should replenishments be performed? How often and when should supplies occur? Lapierre and Ruiz [98] propose an approach to schedule replenishments, purchasing activities, and supplier activities to avoid stock-outs and respect resource availability. The authors formulate a mixed-integer non-linear scheduling problem that balances employees' workload. They develop a tabu search meta-heuristic algorithm for solving the problem.

Scheduling and questions around goods distribution of hospital-internal logistic activities appear to be a promising field for future research. Three potential research areas have been identified. First, the introduction of sophisticated inventory and delivery systems in hospitals raises optimization potential for associated activities. These systems include, for example, mobile medicine closets, twin trolleys, or the 2-bin replenishment system. The motivation behind their introduction derives from hospital-specifics that limit the applicability of standard solutions from other industries. Respective characteristics comprise the limited storage space at point-of-use locations or staff that is untrained in the use of logistics system. Moreover, legislative constraints in drug handling make healthcare specific solutions necessary. A respective use case is presented by Augusto and Xie [7]. The authors schedule pharmacists and transporters used when introducing mobile medicine closets. The case of twin trolleys is discussed by Michelon et al. [119] while Dean et al. [36] optimize the scheduling of pharmacists visits to wards. A topic that has been untouched so far is the 2-bin replenishment system and associated scheduling requirements. Related scheduling activities as when to refill stock and in which overall schedule has not yet been addressed. The work by Lapierre and Ruiz [98] initially covers logistics-related scheduling tasks around hospital inventories. However, many potential areas for optimization remain. Second, as the majority of the presented publications apply heuristics to solve their models, the development of exact solution procedures could further provide interesting research areas. A third promising field is the extension of existing logistics-related scheduling activities to personnel planning and shift planning. Respective questions might appear when logistics activities are transferred to non-medical support staff.

6.2. Hospital-external distribution and scheduling

Hospital-external distribution and scheduling is hardly covered in the literature. In total, there exist five relevant publications including optimization models (see Table 5). They handle inter-hospital transports, transports between suppliers and hospitals, as well as the collection and disposal of waste. In the context of this work, only hospital-related publications are discussed.

Bailey et al. [10] investigate an alternative supply route for time-critical items to hospitals, which usually travel in conjunction with regular goods. They demonstrate that an unattended locker box can serve as an alternative delivery solution for urgent items, allowing the separation of those items from regular material flows. The authors use a hill-climbing optimization algorithm to identify the optimal size of a locker box to cover a certain service level in a typical hospital. Combined with results from staff interviews, they find that the introduction of unattended locker boxes would be beneficial in terms of speed of delivery and healthcare quality. Kergosien et al. [85] address a two-level VRP with time windows, a heterogeneous fleet, multi-depot, multi-commodity, and split deliveries. The first level addresses fleet routing for collection and delivery of pharmaceuticals and hospital consumables. The second level addresses routing employees between hospital unit buildings and sizing of warehouse employees. To solve the problem, two metaheuristic algorithms are presented, a genetic algorithm and a tabu search algorithm. Swaminathan [153] discusses the allocation and distribution of scarce drugs to 150 hospitals in California. Therefore, an optimization model is developed that is solved based on an allocation heuristic.

The collection and disposal of waste is considered a separate field of research that mainly deals with VRPs. As of its relevance to hospital logistics, publications that cover hospital waste disposal are briefly presented. For more detailed information on waste collection and waste management, we refer to the literature review by Beliën et al. [14]. Medaglia et al. [116] design a hospital waste disposal network in Columbia. They formulate the problem as a bi-objective obnoxious facility location problem (BOOFLP) that incorporates the tradeoff to find the cost-optimal facility locations and the negative effects on the population close to waste treatment facilities. They solve their model with a multi-objective evolutionary algorithm. Shih and Chang [150] develop a periodic VRP to model a routing and scheduling problem for the collection of infectious hospital waste. They develop a MIP to assign routes to particular days of the week in a second step. An overview of infectious waste management of European hospitals is provided by Mühlich et al. [120].

Three potential future research areas have been identified: First, it could be promising to assess the robustness of the presented VRPs and its modifications, e.g., through the application of discrete-event simulation as proposed by Kergosien et al. [85]. Second, referring to

Table 5
Hospital-external distribution and scheduling publications containing optimization models.

Publication	Problem description	Model characteristics	Objective function	Type of goods
Bailey et al. [10]	Feasibility demonstration of unattended locker box delivery system; specification of locker box characteristics	Hill climbing optimization algorithm	Maximize number of orders to be stored within locker box	Urgent items
Kergosien et al. [85]	Transportation flow design between hospital units; warehouse employee dimensioning	2-VRP sol. w. meta-heuristics (generic alg. and tabu search)	Minimize the sum of delays and minimize required number of employees	Pharma-ceuticals, consumables
Medaglia et al. [116]	Optimal facility location for hospital waste treatment network	Biobjective facility loc. prob. (MIP), sol. with heuristic	Multiobjective: (1) Minimize transport. cost (2) Min. affected population	Waste
Shih and Chang [150]	Route and schedule for periodic waste collection of hospital network	PVRP and MIP to assign routes to days of week	(1) Minimize transportation cost (2) Minimize daily travel mileage in a week	Waste
Swaminathan [153]	Decision support for allocating scarce drugs to hospitals	Multiobjective optimization model, solved with heuristic	Minimize total value of drug budget left over / maximizing total value of allocated drugs	Pharma-ceuticals

Section 5.2, where we identified hospital layout planning as one potential future research area, incorporating inter-hospital transportation issues into layout planning could be a promising future research field. Third, emergency deliveries within hospital networks could furthermore be assessed within this context.

6.3. Sterile medical devices

The handling of sterile medical items is a distinct field of research within hospital distribution and scheduling. Fineman and Kapadia [46] were among the first to address this problem in the OR literature. For a brief introduction into sterilization logistics, see Di Mascolo and Gouin [107]. There are two kinds of sterile medical items, single-use and reusable medical items. We consider the latter because of the complexity of the repetitive sterilization process, which is omitted for single-use items. Typically, reusable sterile items such as surgical instruments are sterilized after usage in either a hospital-internal sterilization department or by external service providers.

An overview of publications in this research stream applying optimization models is presented in Table 6. The washing process itself is assessed by Ozturk et al. [130], which they claim to be the bottleneck of the sterilization process. They provide a branch and bound based heuristic in order to optimize the washing machine schedule. van de Klundert et al. [90] state that hospitals intensively attempt to outsource sterilization activities in order to save costs and free space in the central sterilization service departments (CSSDs). Outsourcing, however, comes with downsides, for example longer transportation distances and potentially lower availability. In their work, the authors formulate an optimization problem aiming for cost minimization of inventory and transportation costs as a lot sizing and transportation model, which is solved in polynomial time by dynamic programming. Further, they extend the model to a dynamic, non-deterministic setting addressing the value-added of real-time information availability, e.g., when applying RFID. Additionally, they present a bundling problem regarding the composition of medical item nets. Tlahig et al. [155] assess two different setups of sterilization services. They compare decentralized in-house sterilization versus centralized sterilization services in a hospital network. In their model, they aim to find the general setup (centralized vs. decentralized), the optimal location, and the optimal capacity. The problem is modeled as a MIP and solved based on the addition of appropriate cuts. Di Mascolo and Gouin [107] also aim at improving sterilization services within hospitals. They assess the implications of changes in processes and the organization. Therefore, they develop a generic discrete-event simulation model, allowing the authors to represent and quantify any sterilization service in the respective health establishment in France.

Future research may focus on further assessing the performance of different sterilization services in hospitals [107], as well as different organizational setups. These include mixed forms, where some sterile items might be treated within the hospital, while others are sent to external service providers [155]. Also, the incorporation of uncertainty in scheduling the washing process seems to be a worthwhile research field [130].

7. Literature on topic: (4) Holistic supply chain management

Publications regarding the management of the entire supply chain are presented in this section. They do not contain optimization models, but are qualitative or conceptual. Consequently, all presented areas offer new perspectives of incorporating and developing optimization models. We classify the publications into three categories. "Business process redesign" covers all topics associated with the assessment and redesign of logistics processes and the organization of the hospitals' logistics function. "Transfer of logistics concepts from other industries" presents publications that assess if logistics concepts that are successfully implemented in other industries, such as lean, can be transferred to hospital logistics. The final part "Benchmarks, best practices, and cost analyses" discusses practice-related publications, mostly case studies that assess logistics costs and its components, as well as cost comparisons across countries or within hospital departments. The major discussion points and most relevant conclusions are presented.

7.1. Business process redesign

In this section, publications are presented that aim at improving hospital business processes. Therefore, several approaches according to the literature are shown and tools are presented. Generally, it is accepted that logistics processes in hospitals bear significant cost improvement potential. One relevant lever is to redesign logistics processes through implementing SCM practices (e.g., [61,94,138,164]).

Landry and Philippe [97] generally consider the role of logistics and show how it can service healthcare and improve the quality of care. A variety of publications focuses on reengineering the hospital-internal logistics processes, which are the major weak point in hospital logistics [22,30,79]. Chandra [28] discusses trends, issues, and solution techniques for hospital SCM and presents a generic supply chain problem modeling methodology. Kriegel et al. [93] evaluate what role external contract logistics service providers can play in the German hospital sector. Iannone et al. [72] and Zheng et al. [171] assess the potential of the supply chain integration

Table 6
Sterile devices publications containing optimization models.

Publication	Problem description	Model characteristics	Objective function	Type of goods
Ozturk et al. [130]	Near optimal parallel job batch definition for washing step of sterilization process for sterile medical devices	Heuristic based on branch and bound	Minimize makespan of sterilization process	Sterile medical devices
Tlahig et al. [155]	Comparison of decentralized in-house vs. central sterilization service of hospital network	MIP, solved via addition of approp. customized cuts	Minimize total cost (transportation, sterilization, resource transfer, acquisition)	Sterile medical devices
Van de Klundert et al. [90]	Sterilization cost minimization (transportation and inventory costs) for outsourcing sterilization of medical devices	Dynamic programming	Minimize total cost	Sterile medical devices

through enhanced IT integration, e.g., data and information sharing. This enables a higher visibility of inventory data and a reduction of lead times and safety stock. In order to analyze the healthcare supply chain, several tools are on hand to support the decision making process. The tools comprise process modeling techniques [106,71,94] and simulation techniques [2,81].

7.2. Transfer of logistics concepts from other industries

Whether logistics concepts that have successfully been implemented in other industries, e.g., car manufacturing or retail, are transferable to the healthcare sector, is an intensively debated topic in the literature. Most publications conclude that generally, these concepts are applicable in healthcare, but there are major obstacles that need to be overcome. Young et al. [168] very broadly discuss the applicability of industrial processes to healthcare, i.e., lean thinking, theory of constraints, six sigma, and scenario simulation. They conclude that all concepts are applicable in the healthcare sector. However, they state that improvements are not to be expected immediately, but will typically need to undergo an iterative implementation process in order to be successful.

Lean thinking emerged in operations in the beginning of the 1990s, in service operations management around mid/end 1990s, and entered the healthcare sector in the early 2000s [99]. The applicability of lean thinking to healthcare, not necessarily related to material logistics, is conceptually discussed by de Souza [151], Fillingham [45], Kim et al. [87], Kollberg et al. [91], Mazzocato et al. [111], and Young and McClean [169]. These authors find that lean thinking has been applied successfully for a wide range of healthcare applications, but while lean thinking usually takes a holistic approach to problems, healthcare often remains limited to narrower applications with limited organizational reach [111]. Although there seems to be a general agreement on the potential of lean healthcare, it remains challenging to quantify the potential and assess its impact critically. Compared to other industries such as the automotive industry, healthcare lags behind regarding the implementation of lean concepts [151]. Also, a clear definition of the term value is missing in healthcare, hindering the reduction of non-value adding activities, as is standard in industry operations [169]. However, Kim et al. [87] rather optimistically conclude that in the healthcare sector, especially in hospitals, lean thinking can provide significant process improvements and thus improve the quality and efficiency of patient care. A range of publications encompasses case studies where lean concepts have been implemented in healthcare. Trägårdh and Lindberg [156] provide a study of a lean production inspired transformation project in the healthcare sector in Sweden. Landry and Beaulieu [96] present the case of a two-bin Kanban system for point-of-use inventories and discuss its implications to the inventory system. Venkateswaran et al. [160] show that through performing the 5S (sort, set to order, shine, standardize, and sustain) methodology in hospital warehouses, significant increases in inventory turnover can be achieved. 5S represents activities that are required to create a desired work environment. Varghese et al. [159] assess whether actual usage inventory management practices used in the retail industry are applicable in healthcare inventory systems. In particular, they evaluate whether ABC classification, demand characteristics classification, forecast-based demand planning, and inventory control policies are beneficial in the healthcare setting. They create a mathematical model that assesses the possibility to optimize parameters for a (s, Q) inventory policy, based on actual usage inventory management practices and real data. The authors conclude that by applying those concepts, cost improvements may be achieved.

The applicability of JIT to healthcare logistics is assessed in several publications. Jarrett [78] states that the healthcare industry had not implemented JIT at that time and provides examples from the literature to prove this point. Already very early, Kim and Schniederjans [89] demonstrate that JIT or stockless material management can significantly improve hospital operations. Heinbuch [64] provides a case study for the successful implementation of JIT in the hospital sector and proves that significant cost improvements are achieved. Whitson [166] even argues that materials management in the hospital's pharmacy would be an ideal candidate for implementing JIT due to its manufacturing-like operations characteristics. Jarrett [77] again underlines the general transferability of JIT concepts to the healthcare sector but claims that there exists a research gap regarding the actual implementation of JIT in healthcare. Organizational modification to support the introduction of JIT are presented by Yasin et al. [167]. Contrary to the previously presented papers, Danas et al. [34] argue that JIT can hardly be applied in healthcare due to the unpredictable nature of patient mix and the resulting product demand which is hard to forecast. Kumar et al. [95] state that one reason why the healthcare sector has been slow in embracing SCM practices compared to other industries is the danger of stock-out situations to the health of patients.

More broadly, a variety of publications assesses if SCM practices from other industries can be applied in the healthcare sector. De Vries and Huijsman [165] identify five future research areas in healthcare SCM based on a review of the literature: First, the future role of information technology. Second, the influence of different stakeholders on establishing SCM relationships within and between health service providers. Third, to understand strengths and weaknesses of management philosophies like lean/agile manufacturing, business process management, and lean six sigma. Fourth, to define performance metrics of healthcare SCM, and fifth, to apply SCM techniques not only to logistics, but also to patient flow. Ford and Scanlon [48] discuss SCM performance measurements and supplier contracting principles including the applicability to healthcare. Meijboom et al. [117] assess the applicability of SCM practices to patient care. McKone-Sweet et al. [113] find that while the importance of SCM in healthcare is widely recognized, there is only limited research on the unique challenges of healthcare SCM. Operational, organizational, and environmental barriers that hinder the implementation of SCM in healthcare are presented.

7.3. Benchmarks, best practices, and cost analyses

Several practice-related publications, mostly in the form of case studies, compare cost characteristics across hospital departments, different countries, etc. and provide benchmarks for the hospital logistics costs setup. Aptel and Pourjalali [6] compare logistics costs and differences in hospital SCM of large hospitals between France and the U.S. Pan and Pokharel [131] investigate logistics activities of hospitals in Singapore and specifically assess what kinds of activities are performed by the logistics departments. The same field of research is covered by Dacosta-Claro [33] who studies the tasks and management approaches of hospital materials managers. Ferretti et al. [44] assess implications of reorganizing hospital materials processes and organization, while Kafetzidakis and Mihiotis [83] more generally evaluate the awareness of logistics in hospitals in Greece. Potential future research could include a global benchmarking tool that allows for comparison of different logistics setups as well as knowledge transfer and transfer of lessons learnt.

8. Conclusion

The healthcare sector in general and hospitals in particular face significant challenges due to steadily increasing healthcare costs. In hospitals, logistics-related costs are the second largest cost block after personnel costs. In order to reduce material-related logistics costs, healthcare academics as well as practitioners have acknowledged the potential of applying quantitative methods. These methods have already proven their potential in other industries, such as manufacturing or service industries, but need to be modified to account for healthcare specific problem settings. Moreover, the existence of several implementation difficulties is obvious due to the operational complexity of hospital logistics as well as organizational barriers. Further, staff entrusted with logistics activities in hospitals often has no logistics background, which makes implementation of sophisticated concepts difficult. Optimal solutions are overruled or tend to be policy- and experience-driven rather than data-driven.

The purpose of this paper is to present the state-of-the-art of research in hospital materials logistics with a specific focus on publications applying quantitative methods. A comprehensive literature review is conducted. Our contribution is threefold: First, we provide guidance for researchers by categorizing the literature and identifying major research streams. Second, we methodologically discuss the publications and third, we identify future research directions. Four major research fields are identified of which three, i.e., (1) Supply and procurement, (2) Inventory management, and (3) Distribution and scheduling apply optimization techniques. The remaining identified research field, (4) Holistic supply chain management, comprises a rather qualitative field of literature. In total, 145 publications are identified, categorized, and discussed thematically and methodically. The largest thematic category in terms of number of publications is (2) Inventory management (66 publications) over the entire time span, followed by (4) Holistic supply chain management (38 publications), (1) Supply and procurement (25 publications), and (3) Distribution and Scheduling (16 publications), respectively. The number of publications in the field of hospital logistics has been growing over the last years. For example, during the previous three years, the total number of publications nearly doubled compared to the years before. Apart from its relevance for academics, the results of this publication and the overview it provides should also be of interest for practitioners in hospital material management functions.

Hospital materials management is a constantly growing field of research in which further promising research opportunities exist. Opportunities are presented in detail in the respective sections. Summarizing, we identify five overarching research possibilities: First, when integrating the four identified major research streams with applied methodologies, it becomes apparent that the field of (4) Holistic supply chain management offers further research potential with regards to the application of quantitative techniques. So far, integrated optimization across the entire supply chain has not yet been performed in the hospital logistics context. Second, answering the question on how to measure performance in hospital logistics is also a promising future research opportunity. Metrics from other industries, e.g., throughput time, are not directly applicable to hospital logistics as they do not take into account the patient care specifics. Third, future research should continue to incorporate the healthcare and hospital view into operations management and transfer established concepts from other industries into healthcare while accounting for industry specifics. Doing this, it is of pivotal importance to adjust research according to regional specifics due to the high importance of national legislation and strongly regulated nature of the healthcare industry. Fourth, it could be worthwhile to assess which enablers exist that could further push the implementation of sophisticated logistics concepts in hospitals. Potential enablers include consistent information technology systems and data standards across hospitals, clearly defined data interfaces between hospitals and their suppliers, or the introduction of uniform RFID technology. Fifth, in this context, it could be worthwhile to more specifically assess why healthcare has not yet reached the same professional level as other industries and to identify and evaluate potential implementation barriers. However, as healthcare is lacking behind regarding the implementation of quantitative tools as well as SCM practices, other more successful industries should stand as an example for future research.

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